Gas density and star formation in the rarified regions of discs of normal and LSB galaxies

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We calculated the radial profiles of the azimuthally averaged midplane gas volume density ρ_g for 11 high surface brightness (HSB) spiral galaxies, 7 low surface brightness (LSB) galaxies and 3 S0 galaxies assuming their gaseous layers to be in the equilibrium state in the plane of marginally stable stellar discs. We compared the surface star formation rate (Σ_{SFR}) and star formation efficiency ($SFE = \Sigma_{SFR}/\Sigma_{gas}$) with ρ_g and stellar surface density Σ_s assuming the latter to be proportional to disc surface brightness. Both HSB and LSB galaxies follow a single sequence $\Sigma_{SFR} - \rho_g$ and $SFE - \Sigma_s$ or $SFE - \rho_s$. It means that the conditions of star formation are similar in the outer discs of normal spiral galaxies and in the inner regions of LSB galaxies if their stellar discs have similar densities. The relationship between SFE and ρ_s is close to the law $SFE \sim \rho_s^{1/2}$ expected in the theoretical model of self-regulated star formation proposed by Ostriker et al.[1]. The alternative explanation is to propose that SFE is proportional to a frequency of vertical oscillation of gas clouds around the disc midplane. In the most rarified regions of LSB galaxies the efficiency of star formation is nearly independent on gas and stellar disc densities being higher in the mean than it is expected from the extrapolation of the power law fit for HSB sample galaxies. Evidently in these regions with extremely low ρ_g SFE depends on local density fluctuations rather than on the azimuthally averaged disc parameters.

I. INTRODUCTION

Star formation is the main process governing the evolution of galaxies. Star formation rate (SFR) is connected with the amount of gas in galactic discs, although the relationship between SFR and gas mass or gas density is ambiguous and poorly understood. It is clear that local gas density, averaged over large enough area, or azimuthally averaged surface density at a given radial distance R is not the only factor which determines the current

SFR. Indeed, SFR may be different in the inner regions and in the outer regions of galactic disks even for similar surface density of gas because local properties of stellar disc and interstellar medium vary along the radius: a thickness of gas layer increases, a density and internal pressure of gas decreases parallel with its metallicity. Some dynamical parameters such as the angular velocity of rotation also change along the radius. Despite all these complexities, there exist simple, although not very tight, empirical relationships, known as the Schmidt or Schmidt-Kennicutt laws or their different modifications, linking the rate of star formation per unit surface area of a disc Σ_{SFR} (both local or azimuthally averaged one) with a surface density of gas Σ_g at a given distance R from the center (see f.e. [2–7] and references therein). In a wide range of Σ_g the relationship may be written as $\Sigma_{SFR} \sim \Sigma_g^N$, where $N \approx 1.5$. The value of N has a tendency to be higher (the slope becomes steeper) for the atomic gas-dominated outer disc regions, although the scatter of points is large there.

A special problem is to explain how do stars form in the conditions of very low surface density of gas which exists at the peripheral regions of disks of high surface brightness (HSB) spiral galaxies, in some gas-poor lenticular galaxies and in low surface brightness (LSB) galaxies. In all these cases the surface density of gas is too low for the development of gravitational and/or thermal gas instabilities (at least for the usually adopted properties of interstellar medium). Nevertheless, as UV observations of GALEX and Hα imaging showed, a presence of young stellar population in many spiral galaxies is noticeable up to the optical radius R_{25} and even beyond (see [8, 9] and references therein). The origin of the fireplaces of star formation there remains puzzling.

To describe how favorable are the existing conditions for the current formation of stars it is convenient to use the efficiency of star formation SFE, that is a star formation rate per unit of gas mass: $SFE = \Sigma_{SFR}/\Sigma_g$, or gas consumption time $\tau = SFE^{-1}$. As observations show, SFE monotonically decreases along the radius parallel with the gas or stellar surface densities – at least in the outer parts of galaxies [3, 5, 6, 8, 10, 11]. Note that the relationship between Σ_{SFR} and Σ_g or $\Sigma_{\rm HI}$ in the outer parts of discs strongly differs for different galaxies. In some cases there is a break in radial profile of UV or Hα brightness, expected in theoretical models (see f.e. Goddard et al. [9]), but in some galaxies the slope remains nearly constant down to extremely low gas density. A crucial role in star formation in low density regions may belong to a heating of gas by newly formed stars or some outer sources: the indirect evidence of their presence is that the line-of-sight velocity dispersion of HI remains high

enough (5-10 km/s) even at the far peripheries of galaxies [12].

Observations of CO emissions give evidence that the current SFR is in general linearly proportional to the molecular gas surface density $\Sigma_{\rm mol}$ down to a several solar masses per pc^2, although the scatter remains high [7, 13]. It means that SFE, as we define it, just reflects the fraction of molecular gas, or, in other words, a condition of formation and survival of molecular clouds – predecessors of young stars. A correlation of Σ_{SFR} with neutral gas density $\Sigma_{\rm HI}$ is not so well defined as that with molecular gas, but it really exist, especially in the outer regions of discs, where both $\Sigma_{\rm mol}$ and $\Sigma_{\rm mol}/\Sigma_{\rm HI}$ are low. For LSB galaxies, a comparison of total SFR with the total mass of gas shows that SFR is significantly below the extrapolated power law fit applied to the HSB sample (see Wyder et al[14]).

The quantitative analysis and interpretation of these relationships is complicated by the fact that the surface gas density is the integral of volume density along the line of sight, and, hence, even after correction for disc projection, it depends on the thickness of gas layer which changes significantly along the radius of a given galaxy. This circumstance is often ignored, which may lead to significant systematic errors. As we showed in the previous paper (Abramova, Zasov [15]), if to replace the surface gas density Σ_g by the midplane volume gas density ρ_g calculated in the frame of axisymmetric equilibrium disc model, the relationship between Σ_{SFR} and ρ_g becomes more tight and well defined (see Figures 1a,b in this paper) which proves that fundamental relationship is between the Σ_{SFR} and gas volume density, not the surface one.

In this paper we try to compare the efficiency of star formation SFE and its dependence on the volume midplane density of gas and stars in spiral galaxies, LSB galaxies and a few S0-galaxies with noticeable star formation.

II. MIDPLANE GAS DENSITIES

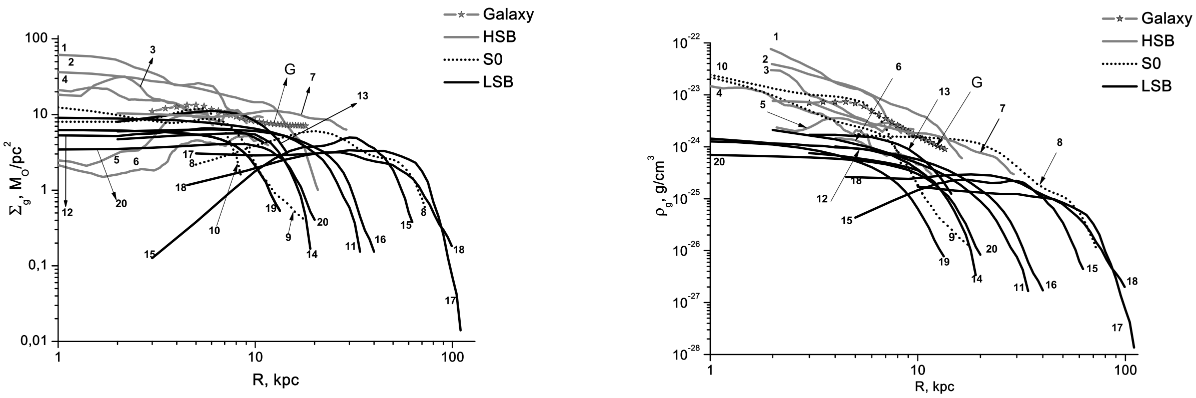
The method of estimation of midplane gas and star densities ρ_g, ρ_s was described earlier (see Abramova, Zasov [15, 16]). We used the velocity curves of galaxies and the radial distributions of brightness and surface gas densities taken from the literature as the input data. The inner regions of galaxies ($R < 1 - 3$ kpc) were not considered – mainly to avoid the influence of a bulge or a bar. The main assumptions we accepted for calculations are counted below:

- gaseous layer and exponential stellar disc are assumed to be axisymmetric;
- gaseous layer and stellar disc are in the vertical equilibrium state situated in the gravitational field of all components of a galaxy (stellar disc, HI and H_2 layers, and spherical pseudo isothermal dark halo);
- gas velocity dispersion is taken to be ∼9 km/s for HI (if the direct estimations are absent) and 6 km/s for H_2 in HSB and S0 galaxies;
- the local values of vertical stellar velocity dispersion assumed to be proportional to the critical radial velocity dispersion for marginally stable discs which stems from the numerical experiments (see Zasov et al. [17]).

The last assumption of marginal stability of stellar disc is usually valid for spiral galaxies – at least within several radial scalelengths, (see the arguments in [18] and references therein), although its validity for the outer discs and for LSB galaxies is questionable (see the discussion in [15]). At any case, if the disc of a galaxy is actually far from marginal stability (that is, a disc is overheated and hence is thicker than expected), then the meanings of ρ_g and ρ_s obtained by the method we used may be considered as the upper limits. It is worth to note that the estimations of these densities are not sensitive to the adopted values of local surface density of disc Σ_d (which is usually close to Σ_s). A reason of it is very simple: for marginally stable self-gravitating discs the increasing of Σ_d leads to the proportional increasing of velocity dispersion of stars (or gas, if its surface density is higher). In turn, it leads to the increasing of disc thickness h proportional to Σ_d, and, as a result, the midplane volume density, being equal to to $\Sigma_d/2h$, remains nearly the same.

Figs 1(a,b) illustrate the radial profiles of the azimuthally averaged surface density Σ_{SFR} (a) and the volume density $\rho_g(R)$ (b) calculated for 21 galaxies (7 HSB, one HSB + extended LSB disk (NGC 289), 10 LSB and 3 S0). The names of all galaxies are counted in the legend to Fig. 1. References to the sources of the disc parameters we used and the rotation curves may be found in Abramova, Zasov [15, 19]. We assumed $H_0 = 75$ km/s/Mpc.

As one can expect, $\rho_g(R)$ decreases steeper than $\Sigma_g(R)$ due to the flaring of gas layer. A mean volume density of the observed HI in the outskirt of LSB galaxies is exremely low – down to 10^{-27} g/cm^3, that is three orders of magnitudes lower than in the solar circle!



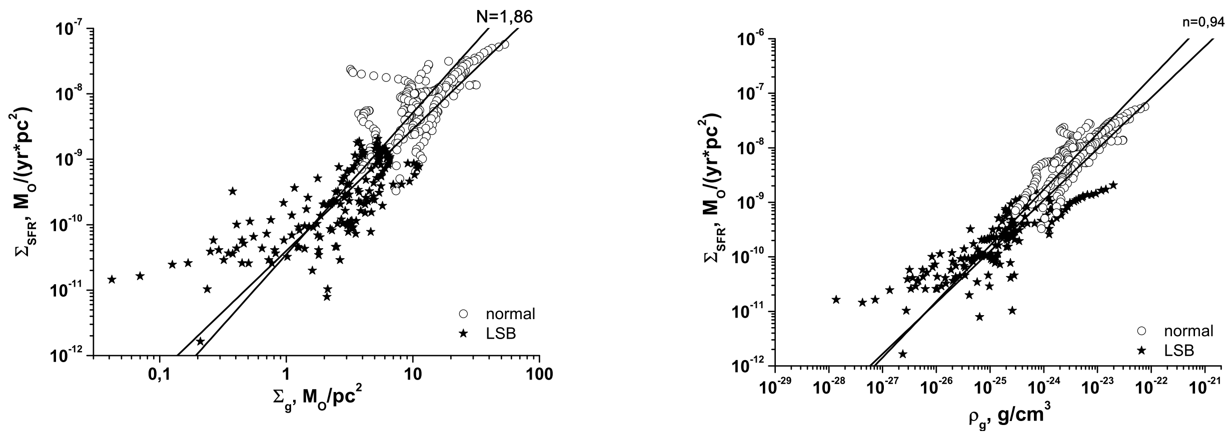
(a) (b)

Figure 1: Radial distribution of surface (a) and volume (b) gas densities for 21 galaxies of different types. *Designations.* HSB galaxies: G - Galaxy, 1 - M51, 2 - M100, 3 - M101, 4 - M33, 5 - M106, 6 - M81, 7 - ngc 289; S0: 8 - ugc 2487, 9 - ugc 11670, 10 - ugc 11914; LSB galaxies: 11 - ugc 1230, 12 - F568-3, 13 - F568-1, 14 - F568-v1, 15 - ugc 6614, 16 - ugc 128, 17 - Malin 1, 18 - Malin 2, 19 - F561-1, 20 - F574-1.

III. STAR FORMATION RATE AND STAR FORMATION EFFICIENCY

To match the midplane gas density with the observed star formation we considered 7 normal galaxies (M33, M51, M81, M100, M101, M106 and Galaxy) and 8 LSB galaxies (F561-1, F574-1, F568-1, F568-v1, F568-3, F568-6 (Malin 2), Main 1 and ugc 6614). The references to the sources of data may be found in [15]. Radial profiles of SFR based on the UV and/or far IR observations for 6 HSBs (except the Galaxy) were calculated as described in [20], the necessary photometric data were taken from Boissier et al [21]. Radial profile of Σ_{SFR} for our Galaxy was taken from the far IR profile $L_{FIR}(R)$ [22] which was normalized to $SFR = 4 \cdot 10^{-9}$ $\mathrm{M}_{\odot}/(\mathrm{yr\,pc}^2)$ in the Solar neighborhood (it corresponds to total $SFR_{tot} = 3,6$ $\mathrm{M}_{\odot}/\mathrm{yr}$).

FUV and NUV profiles based on the GALEX observations which were used to calculate radial profiles of Σ_{SFR} for 8 LSB galaxies were presented by Wyder et al. (2009) [14]. The most reliable and widely used method of estimation of star formation rate is based on the combination of UV (or emission lines) intensity and far infrared brightness to take into account the light absorption. However in the outer regions of galaxies and in LSB galaxies the absorption is low, so the pure UV brightness may be taken as an indicator of SFR [14];



(a) (b)

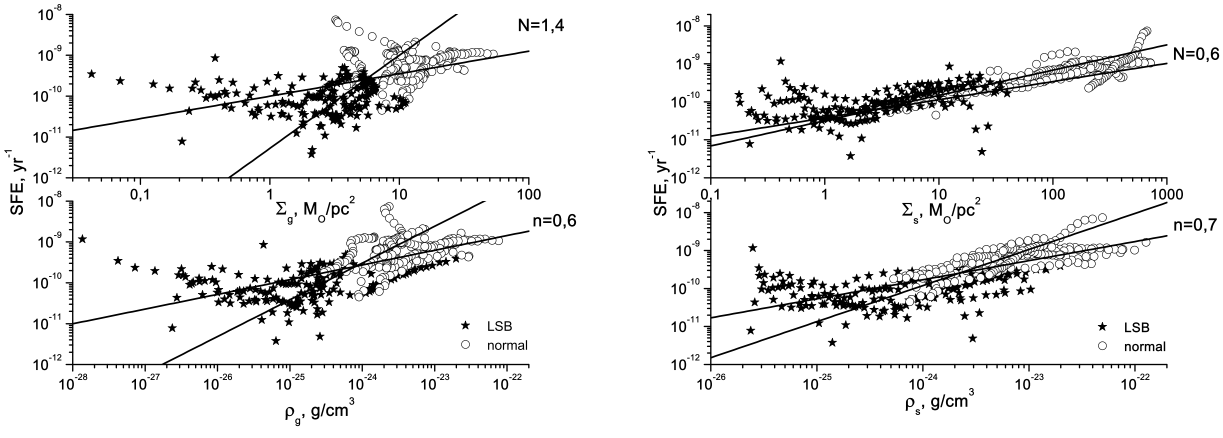
Figure 2: Σ_{SFR} plotted against surface gas density Σ_g (a) and volume midplane gas density ρ_g (b). N and n are the coefficients of bisectors of regression lines.

in general this method gives the bottom estimation of SFR. For LSB galaxies the molecular gas was ignored due to its low content.

It should be remembered that the absolute estimates of SFR are always very approximate and may contain systematic errors, mostly due to the uncertainties of the adopted stellar IMF and the difficulties of taking into account the dust extinction. All indicators of star formation relate mainly to stars of high and intermediate masses. Happily, there are no direct evidences that IMF strongly differs in the inner and in the outer regions of galactic discs [9, 23] or in LSB galaxies [14], which allows to use the existing estimates of SFR for comparison purposes.

In Figures 2a,b the Σ_{SFR} plots as a function of the surface gas density $\Sigma_g = 1.4\,(\Sigma_{\rm HI}+\Sigma_{\rm H_2})$ (a) and the volume gas density ρ_g (b), calculated as described above for normal and LSB galaxies.

A comparison of diagrams (a) and (b) clearly illustrates that Σ_{SFR} correlates with the volume gas density better than with the surface one: correlation coefficients $R = 0.85$ and 0.91 correspondingly, or 0.85 and 0.94 if to exclude LSB galaxy F568-3 which has the outstandingly low Σ_{SFR} for its gas density (see Fig 2(b)). The most essential is that the dependencies for normal and LSB galaxies overlap while continuing each other. It means that the same density of gas provides similar star formation rate both in the outer regions of normal spiral galaxies and in the inner, most gas-rich regions of LSB galaxies. A bisector



(a) (b)

Figure 3: SFE plotted against gas densities Σ_g and ρ_g (a) and stellar disc densities Σ_s and ρ_s (b). N and n are the coefficients of bisectors of regression lines.

between the regression lines, found by the least square method, has the slope n which is close to unit (see Fig. 2(b)). Note that the most rarified regions of LSB galaxies ($\rho_g < 10^{-26}$ g/cm^3) spread very loose on the diagram. In the mean, their Σ_{SFR} is higher than expected. Disc overstability cannot explain it because it would shift the points in the opposite direction. It seems, that the axial symmetry and dynamical equilibrium may not be valid for the strongly rarified outer discs.

Now, to exclude the basic relationship between Σ_{SFR} and gas content, we consider the efficiency of star formation $SFE = \Sigma_{SFR}/\Sigma_g$. As observations show, SFE is usually lower at the disc periphery than in its inner regions both for normal and LSB galaxies (see f.e. [5, 14]). A key factor responsible for the radial declining of SFR may be a decreasing of gas or/and star volume density and gas pressure, along the radius. However a correlation of SFR with gas density looks very loose (see Fig 3(a). The midplane gas pressure $P_g \sim \rho_g V_g^2$ should follow ρ_g(R) due to slow radial variation of gas velocity dispersion V_g, hence both ρ_g and P_g may hardly be the main factors which determine SFE.

Surprisingly, SFE correlates more tightly with the stellar densities of discs – both the surface and volume ones (Fig 3(b)). A connection between the disc stellar surface densities and star formation rate for HSB spiral galaxies was first noted by Ryder and Dopita [24] and later confirmed by other authors ([5, 20]). It appears that the there exist a single

relationship between SFE and Σ_s or ρ_s for both HSB and LSB galaxies covering the range $\Sigma_s = 3 - 300 M_\odot/pc^2$. A comparison of diagrams in the top and in the bottom of Fig 3(b) shows that the correlation may be tighter for the surface stellar disc density than for the volume one, but it may resulted from the different methods of density estimations: Σ_s is directly obtained from observational data, whereas ρ_s is the result of model calculations. A relationship $SFE(\rho_s)$ closely follows the simple law $SFE \sim \rho_s^{1/2}$ or, in general, $(\rho_g + \rho_s)^{1/2}$ (not shown here). Note that a root square of total disc density is proportional to the inverse dynamical time, or to a frequency of crossing the midplane by any disc particle (gas cloud). This oscillation frequency may serve as the universal factor which regulate SFR equally well in high and low density regions if other factors are favorable for star formation.

Another more sophisticated explanation of the nearly root-square relationship follows from the model of self-regulated star formation proposed by Ostriker et al. [1]. In this model a role of key factor for star formation plays UV radiation created by young stars which keeps the thermal pressure of diffuse fraction of gas at the level imposed by vertical force balance. For the diffuse gas-dominated regions the model predicts $\Sigma_{SFR} \sim \Sigma_g \rho_{tot}^{1/2}$, where ρ_{tot} is the total midplane density of matter.

The most rarified outer regions of LSB galaxies ($\Sigma_s \leq 3 M_\odot/pc^2$) hardly reveal any connection of SFE with the gas or stellar disc density at all. For these regions SFE lays within the range $10^{-10} - 10^{-11} yr^{-1}$, which is higher in the mean than it is expected from the sequences which fits the higher gas density regions of HSB spiral galaxies (Fig 3b). Star formation rate in these regions is governed by some other physical factors but the stellar or gas densities. Extremely low level of star formation means that it should be concentrated in a small number of starforming sites with a random local excess of gas density, so it is hard to expect them to follow general correlations. Both stellar and gaseous discs with such low densities may be irregular and far from equilibrium state, which makes the model we use for the density estimations to be unacceptable. Accretion flows, minor mergers or interactions may be responsible for local gas concentrations, as for a great diversity of the observed properties of extremely rarified regions.

IV. CONCLUSIONS

A comparison of star formation rate and star formation efficiency with the disc an gas midplane densities we found for a sample of HSB and LBG galaxies shows that:

- both types of galaxies follow a single sequence $\Sigma_{SFR} - \rho_g$, revealing the common Schmidt law within a wide range of gas densities down to $10^{-25} - 10^{-26} g/cm^3$;
- Star formation efficiency depends on the stellar density Σ_s or ρ_s in a similar way for both HSB and LSB galaxies. Hence for a given stellar and gas densities the conditions of star formation are similar in the outer discs of spiral galaxies and in the inner, most gas-rich regions of LSB galaxies;
- The relationship between SFE and ρ_s is close to the law $SFE \sim \rho_s^{1/2}$ expected in the theoretical model of self regulated star formation developed by Ostriker et al [1]. The alternative explanation is to propose that SFE is proportional to a frequency of vertical oscillation of gas clouds around the disc midplane;
- SFR and SFE in the most rarified regions of LSB galaxies ($\rho_g \leq 10^{-26} g/cm^3$) do not reveal significant correlations with gas and stellar disc densities; the model of equilibrium axisymmetrical disc is hardly applicable for them. Local density fluctuations rather than azimuthally averaged disc parameters should play a crucial role in the triggering of star formation there.

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